NPOESS Conical Microwave Imager/Sounder: RFI Issues and Progress

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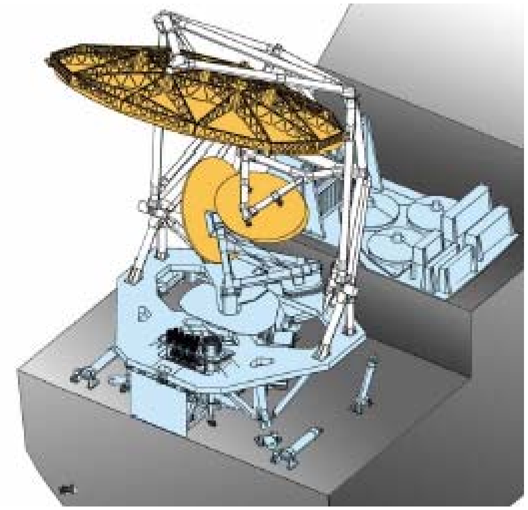

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Outline

- **CMIS sensor baseline design - main features**
- **Environmental Data Records (EDRs) and science algorithms**
- **RFI issues and progress**
  - Hardware mitigation of Radio Frequency Interference
  - Survivability
  - Performance impacts on EDRs especially on soil moisture
- **Ongoing issues and risks**
  - Antenna characterization issue
  - Algorithm performance
  - Watch list items

Primary instrument for satisfying one-third of total number of NPOESS Environmental Data Records (EDRs)

NPOESS EDR and Sensors

☆ Atmospheric Vertical Moisture Profile	Cloud Top Pressure	Precipitable Water
☆ Atmospheric Vertical Temp Profile	Cloud Top Temperature	Precipitation Type/Rate
☆ Imagery	Downward Longwave Radiance (Sfc)	Pressure (Surface/Profile)
☆ Sea Surface Temperature	Downward Shortwave Radiance (Sfc)	Sea Ice Characterization
☆ Sea Surface Winds	Electric Field	Sea Surface Height/Topography
☆ Soil Moisture	Electron Density Profile	Snow Cover/Depth
Aerosol Optical Thickness	Energetic Ions	Solar Irradiance
Aerosol Particle Size	Geomagnetic Field	Supra-Thermal-Auroral Particles
Aerosol Refractive Index	Ice Surface Temperature	Surface Type
Albedo (Surface)	In-*situ* Plasma Fluctuations	Wind Stress
Auroral Boundary	In-*situ* Plasma Temperature	Suspended Matter
Auroral Energy Deposition	Ionospheric Scintillation	Total Water Content
Auroral Imagery	Medium Energy Charged Particles	Vegetation Index
Cloud Base Height	Land Surface Temperature	
Cloud Cover/Layers	Net Heat Flux	
Cloud Effective Particle Size	Net Solar Radiation (TOA)	
Cloud Ice Water Path	Neutral Density Profile	
Cloud Liquid Water	Color/Chlorophyll	
Cloud Optical Thickness	Ocean Wave Characteristics	
Cloud Particle Size/Distribution	Outgoing Longwave Radiation (TOA)	
Cloud Top Height	Ozone - Total Column/Profile	

- VIIRS (25)
- CMIS (19)
- CrIS/ATMS (3)
- OMPS (1)
- SES (13)
- GPSOS (2)
- ERBS (5)
- TSIS (1)
- ALTIMETER (3)
- APS (4)

☆ Environmental Data Records (EDRs) with Key Performance Parameters

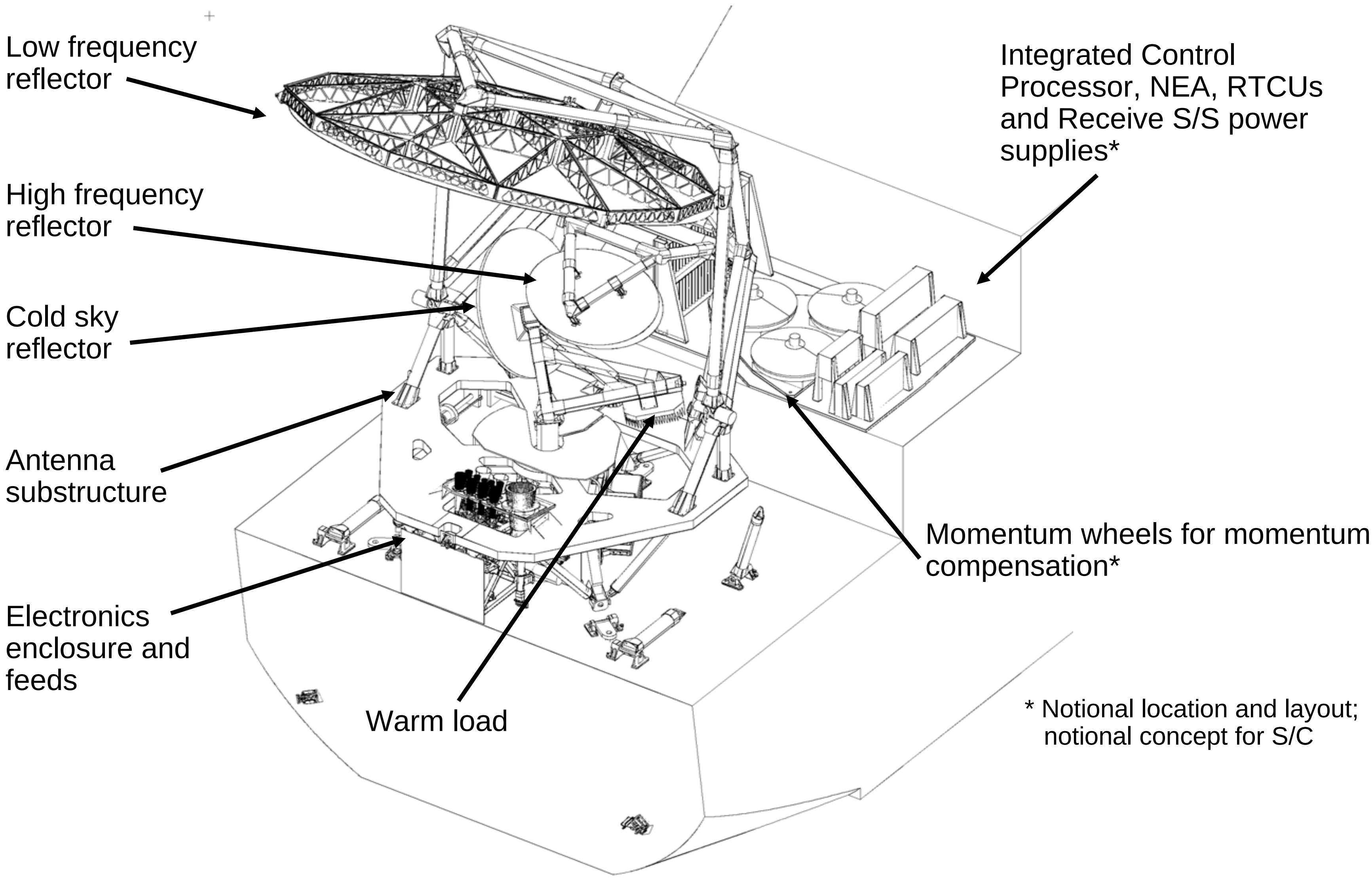
CMIS Design Key Features

- 9 bands from 6 to 183 GHz
- 77 primary and 17 redundant channels
- 16 separate feeds
  - ✓ 12 feed for low frequency reflector (6 to 89 GHz)
  - ✓ 4 feed for high frequency reflector (166-183 GHz)
- Contiguous channel coverage of O_2 line using 40 Fast Fourier Transform

•Deployable low frequency reflector (2.2 m)
•Separate high and low frequency reflectors
•Spinning at 31.6 rpm
•Warm load and cold sky calibration
•Absolute radiometric accuracy <1K

•Pointing performance of 0.9 km along scan and 1.43 km cross scan
•Data Rate: 350 kbps?
•Reliability: 0.91?
•Mass: 387 kg ?
•Operational Power: 328 W ?

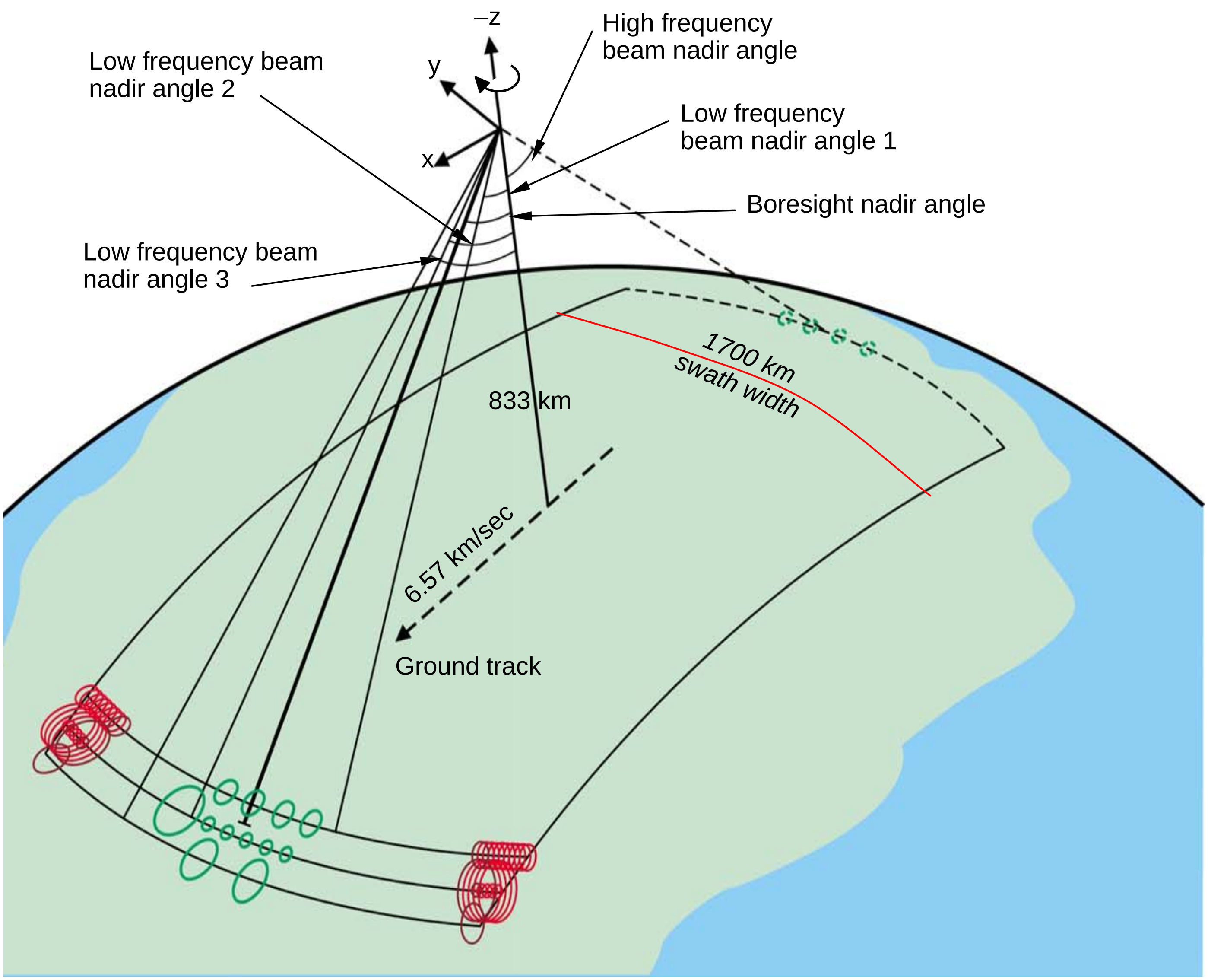
Sensor Deployed Configuration



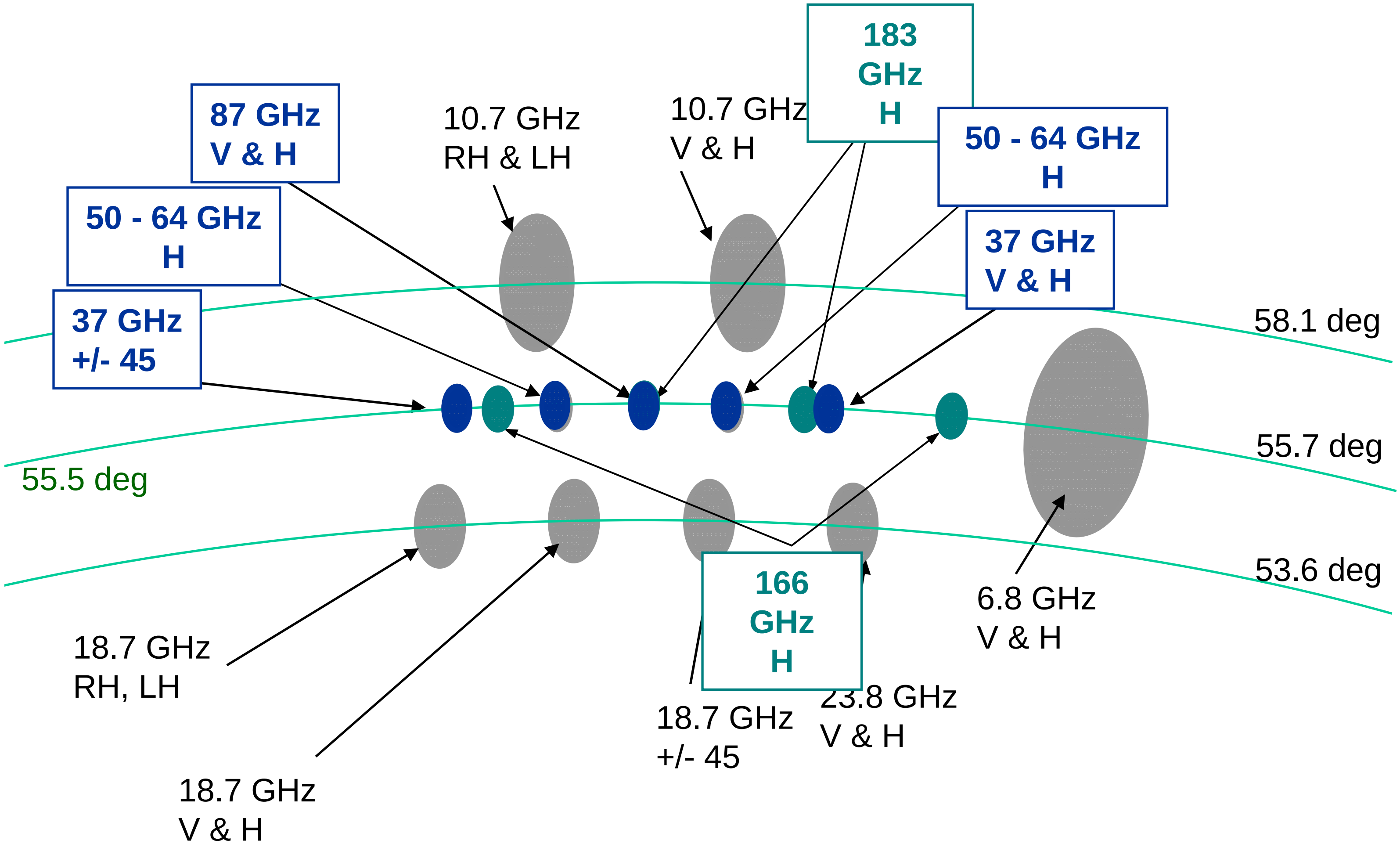
CMIS Mock-up

Comparison with TMI and SSM/I

Scan Geometry

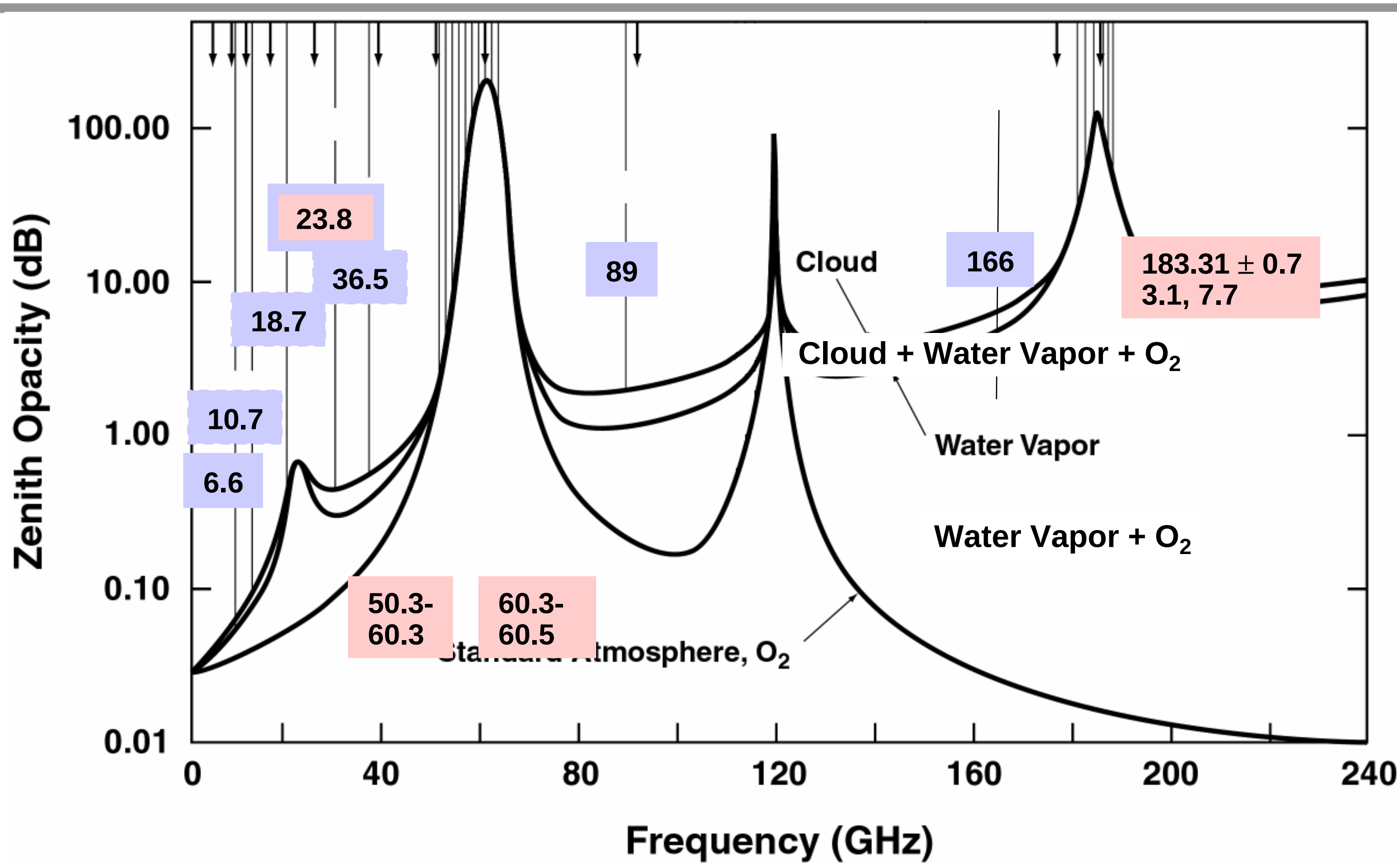


Beam (IFOV) Layout



- All polarizations per frequency are on same arc to support cross-polarization correction
- Functional channel pairs are on common arc to minimize view geometry differences, maximize water vapor performance e.g. 19, 23 GHz and 166, 183 GHz

Frequency Spectrum of Atmospheric Gases
CMIS Channels



☐ Window Channels

☐ Sounding Channels

New (non-heritage) CMIS EDRs

- **Soil Moisture (IA)**
  - Added C-band (2.2m deployable reflector)
  - Risk reduction through AMSR – questionable now due to RFI
- **Sea Surface Wind Direction (IIA)**
  - Added polarimetric channels at 10 (V, H, R, L), 18 (V, H, P, M, R, L) and 36 (V, H, P, M).
  - Risk reduction through Windsat (conically-scanned, 1.83m non-deployable parabolic reflector, polarimetric system , 6 - 37GHz).
- **Stringent requirements on Moisture and Temperature Profiles at higher altitudes (IA &IIA)**
  - Added FFT at 60.4347GHz.
  - Risk reduction demonstration in Phase - I
- ***Cloud Ice Water Path (IIA*)**
  - Current design does not meet threshold requirements
  - Addition of sub-millimeter wave (e.g. 325 GHz) channels will partially meet EDR requirement. Consideration is dropped for now.

CMIS Open Issues
EDRs and Algorithms

- **EDR threshold not met**
  – Ice Surface Temperature (II) - limitations due to natural phenomena
  – Cloud Ice Water Path (II) - not enough channels
- **EDR threshold partially met**
  – Snow Cover/Depth (III) - resolution requirement not met
  – Atmospheric Vertical Temperature Profile (II) - regions <0.02mb
  – Precipitation (II) - weak signal over land
  – Sea Surface Wind Direction (II) - weak signal at low wind speed (<5m/sec)
  – Total Water Content (II) - limited by physics in range >60kg/m2
- **Multiple Radiative Transfer Models -** Quantization of the differences
- **AER Core Module retrieval approach needs to be independently tested**
- **Testing/stratification of EDRs -** global averages vs. stratified binning

Antenna Characterization

•Wind direction EDR requires accurate brightness temperature data collected by CMIS polarimetric channels

- **Baseline approach**
  - Antenna characterization using only near-field approach and use modeling to extrapolate far-field effects
- **Post-baseline work**
  - Design and construction of a simplified scale mock-up (41 inch) antenna
  - Polarization calibration of the feed horns and near-field probes
  - Planar near-field measurement of the mock-up antenna, including far sidelobes
  - Numerical simulation of the mock-up antenna using the GRASP8 computer program
  - Independent check on software code used to compute the Stokes M-matrix given a set of measured (or simulated) antenna patterns.
  - Aerospace is performing all the above tasks using a CMIS mock-up system.

Watch list

- Sensitivity to scattered solar radiations
- Short-term gain stability for high frequency channels e.g. 183 GHz
- EDR performance measure based on global averaging
- Backus-Gilbert processing under gradient conditions
- CMIS all-weather performance – algorithm robustness under higher level of rainfall
- Co-registration of various channels
- Polarization characterization, near field vs. far field
- Calibration of FFT channels
- Frequency set-ability and stability
- BAPTA life test
- Mass margins at all levels

Integrated Operational Requirements Document (IORD) I –Soil Moisture

4.1.6.1.6 ***<u>Soil Moisture (Surface)</u> (<u>*DoD/DOC</u>)**. Soil moisture measurements are needed to derive trafficability information useful for support of the deployment of amphibious and ground forces. Moisture in the soil within the zone of aeration, including water vapor present in soil pores.

<u>Systems Capabilities</u>	<u>Thresholds</u>	<u>Objectives</u>
a. Sensing Depth*	**Surface (skin layer: -0.1 cm)**	Surface to -80 cm
b. Horizontal Cell Size		
1. Clear, nadir	1 km	
2. Clear, worst case	4 km	2 km
3. Cloudy, nadir	40 km	2 km
4. Cloudy, worst case	50 km	
c. Vertical Sampling Interval	Not Required	5 cm
d. Mapping Accuracy, clear, nadir	1 km	0.5 km
e. Mapping Accuracy, cloudy	5 km	1 km
f. Measurement Uncertainty**	Bare soil, in regions with known soil types: 10% (low HCS) 20% (high HCS - clear skies)	Surface: 1% 80 cm column: 5 %
g. Measurement Range	0 -100%	0 -100%
h. Latency	90 minutes	30 minutes
f. Refresh	8 hours	3 hours

**Units are dimensionless and moisture refers to volumetric soil moisture

CMIS Soil Moisture Specification -I

3.2.1.2.1.1.3.1 Soil Moisture

Total liquid water in the soil or in a surface layer over soil. The requirement is to measure soil moisture to within a thin layer at the surface (0.1 cm) for bare soil in regions with known soil types, as well as, soil moisture for vegetated terrain.

Soil Moisture Specification Table

Parameters	Requirement
a. Horizontal Cell Size	≤40 km
b. Horizontal Reporting Interval	≤40 km
c. Vertical Cell Size	≥0.1 cm
d. N/A	N/A
e. Horizontal Coverage	Land
f. Vertical Coverage (TBR)	0 to ≤-0.1 cm
g. Measurement Range	0 - 100%
h. Measurement Uncertainty	8.5%
i. Mapping Uncertainty	≤3 km
j. Swath Width	≥1700 km

Degradation and Exclusions

Soil Moisture:

For 6GHz, RFI >5K and VWC < 0.2kg/m**2	performance degradation: uncertainty increases from 8.5% to 10%, given RFI is detectable
For 6GHz RFI >5K and VWC > 0.2kg/m**2	exclusion i.e. EDR not produced

Sea Surface Temperature:

For 6GHz, 0.1K<RFI<0.4K	performance degradation: uncertainty up from 0.5K to 1K
For 6GHz, RFI>0.4K	exclusion: EDR not produced

Based on AMSR data, soil moisture EDR performance will be severely compromised due to RFI

Soil Moisture R&D Issues

•**Threshold IORD requirements are easy to meet but objective requirements are challenging.**

•**FCS (Future Combat System) 'desirements' for soil moisture involve:**

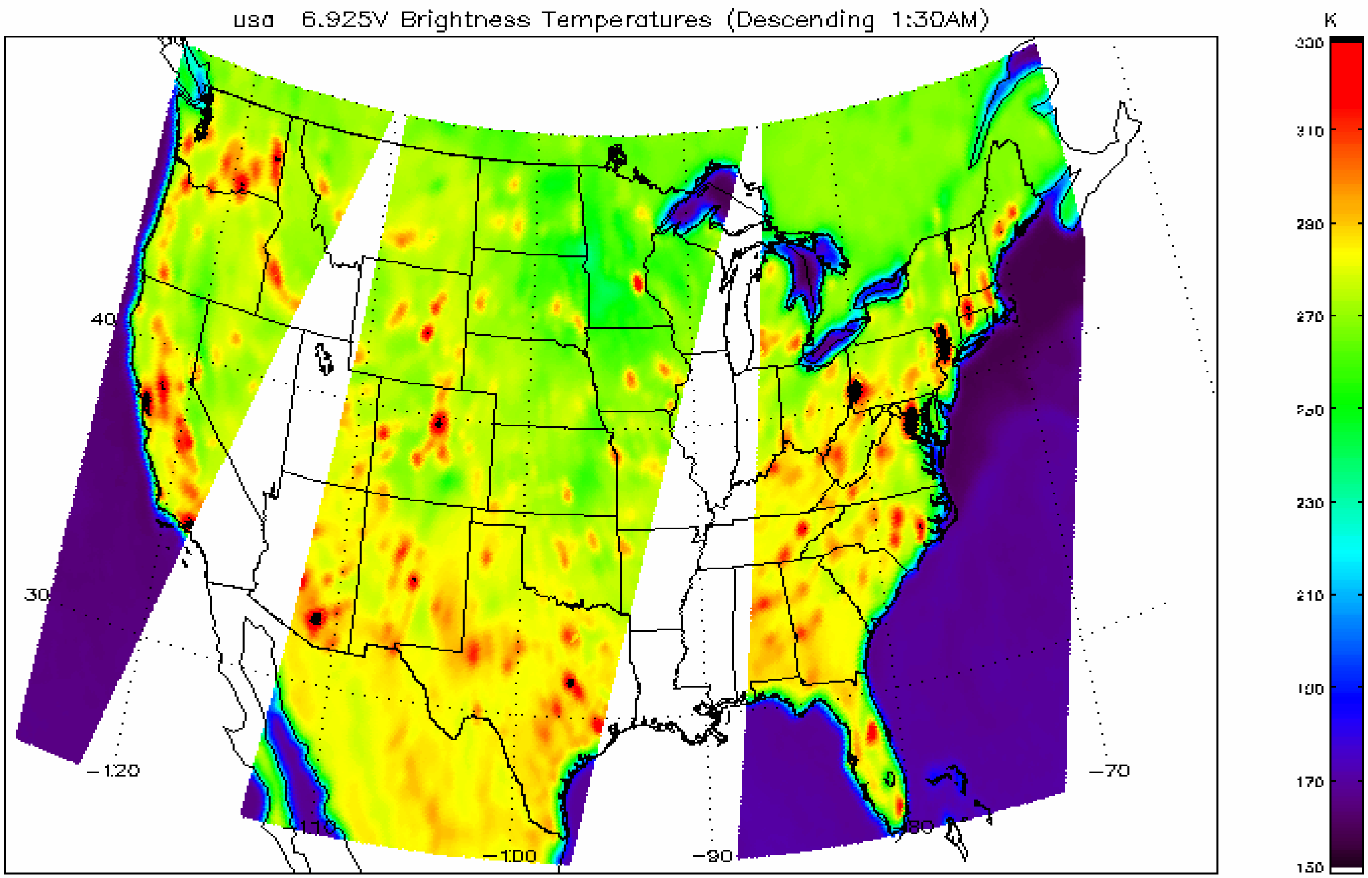
- Increased spatial resolution*
  - Ad-hoc technique based on microwave and optical data fusion to produce soil moisture at HSR of 1-km. Needs more work, testing.
- Soil moisture profile
  - Nothing is planned. IPO may need more push from Army to proceed further on this.
- RFI mitigation for global availability of soil moisture
  - A hardware mitigation technique is in process. Preliminary study completed.
- Mixed pixels
  - Only water bodies are identified. Other heterogeneities such as those due to vegetation, surface roughness, etc. are not addressed.

**** Chauhan N. S. et al., 2003, "Spaceborne soil moisture estimation at high resolution: a microwave-optical/IR synergistic approach", International Journal of Remote Sensing, vol. 24, pp. 4599-4622.***

Overview of CMIS RFI Study

- **RFI Study was intended to explore improvements to the CMIS baseline design so as to lower the risk of Radio Frequency Interference (RFI) and improve survivability.**
  - All RFI/EMI sources such as on-board emitters and out of band ground emitters were considered
    - **Priorities**
      - 1. Survival
      - 2. Operate through On-board transmitters (reviewed in relation to survival)
      - 3. Operate through In-band Ground RFI
      - 4. Operate through Out of Band Ground RFI
- **Three representative RF environments were selected for this study**
- **Approaches for RFI mitigation included FFT, sub-banding, temporal sampling, tunable frequencies, and combinations of these techniques.**
- **Approaches for survivability and operability included review of limiter and filter options**
- **Preliminary results show that**
  - Several potential RFI mitigation approaches yield improvement in EDR performance in the presence of RFI with moderate sensor design impacts
  - Better definition of the CMIS RF operating environment (ground and on-board emitter levels) modifications are needed to ensure optimal performance and design

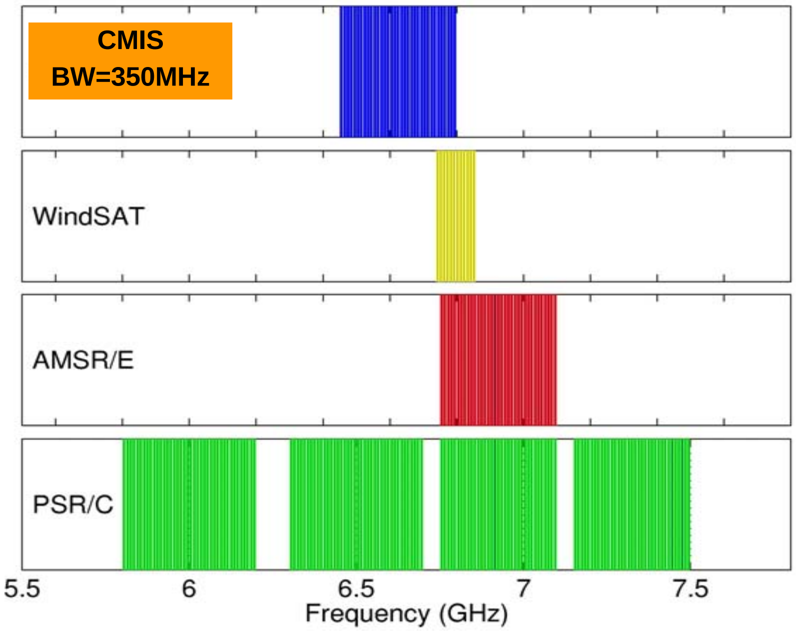
AMSR 6-GHz T_B


usa 6.925V Brightness Temperatures (Descending 1:30AM)
40
30
−120
−100
−90
−70
K
330
310
290
270
250
230
210
190
170
150

On-orbit RFI Impacts at 6 and 10-GHz

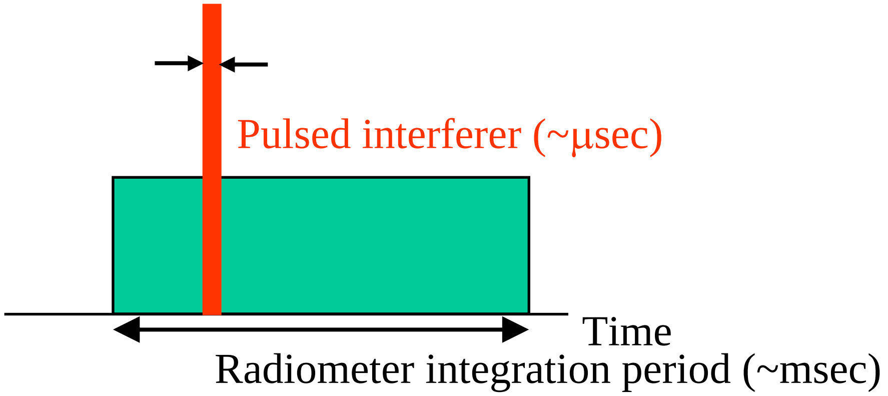
- AMSR and WINDSAT data show increased level of RFI at C and X-band
- No history of RFI mitigation except for aircraft-based PSR
- Interference can be pulsed and non-pulsed
- Signal corruption level and sensor survivability

Spectral interference



C-band Integration time for CMIS= 5.06ms

Temporal interference



Courtesy: Joel Johnson

CMIS Sensitivity to RFI

- **Contamination of Brightness Temperature Measurements**
- **Operate Through**
  - Moderate level (~ microwatts) signals can distort the measured power levels by affecting the linearity of the radiometers response
  - True for signals outside and inside the design bandwidth of the channel
  - Primarily a concern from on-board signal sources
- **Low Level RFI**
  - Very low level signals (~ nanowatts) originating at the Earth's surface will increase the signal level at the detector making the scene appear too warm and causing EDR errors
  - Principal concern is low level ground emitters originating from a variety of radio services operating in the C-band region
- **High Level RFI (Survivability)**
  - High level signal (~milliwatts) can destroy LNA
  - Principal concern is the instrument damage due to 'looking at' these high level ground radar

RFI Mitigations Options For CMIS

- **Several RFI Mitigation Options Were Considered**
  - Option 1: Digitize the channel and perform an FFT to produce multiple narrow band channels
  - Option 2: Analog Sub-banding; consider 4, 5 and 6 sub-bands per polarization
  - Option 3: Over-sampling; divide a single 5 ms sample (6-GHz channel) into several shorter samples
  - Option 4: Combine Option 2 and Option 3 to achieve more robust RFI mitigation
  - Option 5: Tunable 6-GHz Receiver; Implement ability to tune the baseline receiver upon command from spacecraft
  - Option 6: RFI Mitigation at 10-GHz through analog or digital sub banding
- **RFI "Scenes" were supplied by the IPO to evaluate the various options**

RFI Scenes and Analyses

•RFI Scenes Were Supplied to Aid in Evaluating RFI Options for CMIS

- Three Scenes or "Scenarios" were delivered during the course of the CMIS RFI study
- All Scenarios contained multiple low-level emitters in the 6-GHz region
- One Scenario also contained low-level emitters at 10-GHz
- Scenarios contained multiple simulated emitters (up to ~4000) placed on grids of several hundred km in length and width
- No polarization information was supplied and the RFI sources were treated as isotropic for this exercise.

•RFI Analysis Procedure

- CMIS swath was simulated passing over the scenario region
- For each option, EFOV, sub-band, and sub-sample (temporal) the change in brightness temperature due to all RFI sources was computed

Scenes used in the present study represent only a subset of global-annual conditions

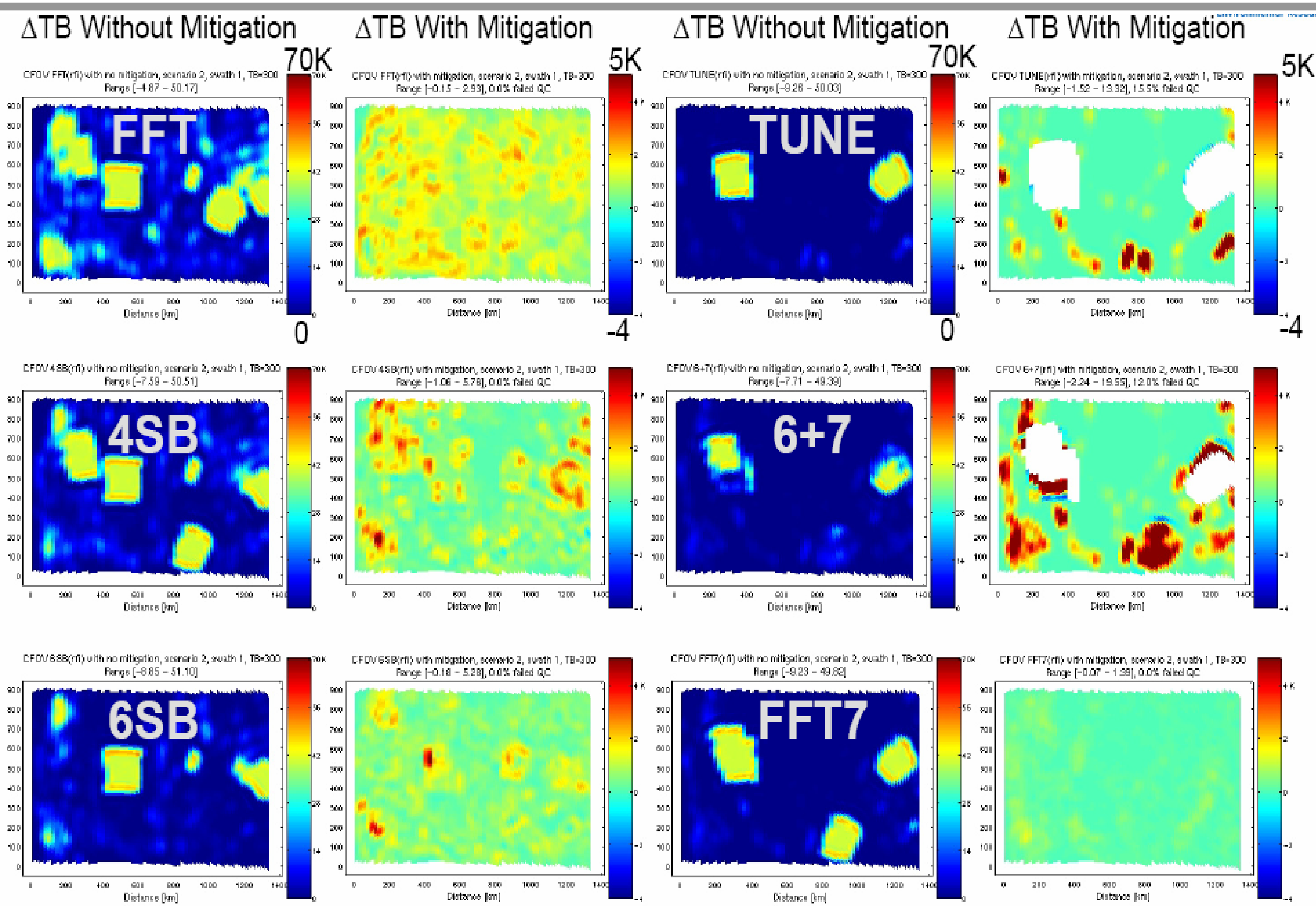
RFI Scenario Analysis Procedure

1. Simulate CMIS swaths passing over the scenario region
2. Project EFOV normalized antenna patterns (F_n) at each scan position (BSS-simulated antenna gain data projected on a 240 km square grid at 6 GHz)
3. Compute gain to each source covered by antenna pattern
4. Compute gain-weighted PSD combining all CW sources
   - For pulsed sources, equivalent CW PSD is calculated for use with options without temporal subsampling
5. For each option, EFOV, subband, and temporal subsample, compute ΔTB due to all RFI sources
   - Pulse source start timing is randomized per EFOV
   - For $P_{t,i}$ power transmitted in subband i with bandwidth Δf_i:

$$\Delta T_{rfi,i} = \frac{1}{\eta_e} \frac{1}{\mathrm{k}\Delta f_i} \mathrm{T}_{atm} \left(\frac{P_{t,i}}{4\pi R^2} \right) \left(\frac{\lambda^2 F_n(\theta_t, \phi_t)}{\Omega_p} \right)$$

$$\text{where} \quad P_{t,i} = 1\mathrm{E}6 \sum_{\Delta f_i} \mathrm{PSD}(f)$$

RFI Scenario 2 Mitigation Test Results



RFI Analysis Results

•The CMIS RFI mitigation options analyzed were found to be generally very effective in reducing the impact of RFI to CMIS

- RFI Mitigation in the 6-GHz spectral region can significantly improve soil moisture retrievals in RFI-contaminated regions
- All proposed 6-GHz RFI mitigation options can significantly improve soil moisture retrievals
  - Options 1 (FFT) and 2 (spectral sub-bands) improve soil moisture in all RFI conditions tested
  - Option 5 improves soil moisture in most conditions tested; it was difficult to simulate scenarios to show advantages of tunability
- Proposed 10-GHz RFI mitigation option can improve soil moisture retrievals but only in some RFI conditions
- Other EDR impacts of proposed design changes
  - SST: Some options degrade precision
  - AVMP: Some options degrade land/cloudy conditions

BACK-UP SLIDES

CMIS Channel Set

Low Frequency (6- 89 GHz) Reflector Channels

Channel	Center Frequency, GHz	Bandwidth, MHz
6V, H	6.625	350
10V, H, R, L	10.65	100
18V, H, P, M, R, L	18.7	200
23V, H	23.8	400
36V, H, P, M	36.5	1000
60VA	50.3	134
60VB	52.24	1280
60VC	53.57	960
60VD	54.38	440
60VE	54.905	350
60VF	55.49	340
60VG	56.66	300
60VJ	59.38	280
60VK	59.94	440
60LL	60.3712	57.6
60LM	60.408	16
60LU	60.4202	8.4
60LV	60.5088	44.8
89V, H	89	4000

CMIS Channel Set

Fast Fourier Transform (1- 20) Channels

Channel	Center Frequency, GHz	Bandwidth, MHz
60L FFT 1	60.425526	1.5
60L FFT 2	60.426901	1.25
60L FFT 3	60.428026	1
60L FFT 4	60.429026	1
60L FFT 5	60.429901	0.75
60L FFT 6	60.430526	0.5
60L FFT 7	60.431026	0.5
60L FFT 8	60.431526	0.5
60L FFT 9	60.431901	0.25
60L FFT 10	60.432151	0.25
60L FFT 11	60.432401	0.25
60L FFT 12	60.432651	0.25
60L FFT 13	60.432901	0.25
60L FFT 14	60.433151	0.25
60L FFT 15	60.433401	0.25
60L FFT 16	60.433651	0.25
60L FFT 17	60.433901	0.25
60L FFT 18	60.434151	0.25
60L FFT 19	60.434401	0.25
60L FFT 20	60.434651	0.25

CMIS Channel Set

Fast Fourier Transform (21- 40) Channels

Channel	Center Frequency, GHz	Bandwidth, MHz
60L FFT 21	60.434901	0.25
60L FFT 22	60.435151	0.25
60L FFT 23	60.435401	0.25
60L FFT 24	60.435651	0.25
60L FFT 25	60.435901	0.25
60L FFT 26	60.436151	0.25
60L FFT 27	60.436401	0.25
60L FFT 28	60.436651	0.25
60L FFT 29	60.436901	0.25
60L FFT 30	60.437151	0.25
60L FFT 31	60.437401	0.25
60L FFT 32	60.437651	0.25
60L FFT 33	60.438026	0.5
60L FFT 34	60.438526	0.5
60L FFT 35	60.439026	0.5
60L FFT 36	60.439651	0.75
60L FFT 37	60.440526	1
60L FFT 38	60.441526	1
60L FFT 39	60.442651	1.25
60L FFT 40	60.444026	1.5

CMIS Channel Set

High Frequency (166- 183 GHz) Reflector Channels

Channel	**Center Frequency GHz**	**Bandwidth MHz**
166V	166±0.7875	1425
183VA	183.31±0.7125	1275
183VB	183.31±3.10	3500
183VC	183.31±7.70	4500

CMIS EDR Requirements Prioritization

(EDRs listed alphabetically within Threshold category)

EDR	Threshold	Objective
Atmospheric Vertical Moisture Profile (0 to 600mb)	I	A
Sea Surface Winds (Speed)	I	A
Soil Moisture	I	A
Atmospheric Vertical Moisture Profile (remaining)	II	A
Atmospheric Vertical Temperature Profile	II	A
Cloud Ice Water Path	II	A
Cloud Liquid Water	II	A
Ice Surface Temperature	II	B
Land Surface Temperature	II	B
Precipitation	II	A
Precipitable Water	II	A
Sea Ice Age and Sea Ice Edge Motion	II	B
Sea Surface Temperature	II	A
Sea Surface Winds (Direction)	II	A
Total Water Content	II	A
Cloud Base Height	III	B
Fresh Water Ice	III	B
Imagery	III	B
Pressure Profile	III	B
Snow Cover	III	B
Snow Depth	III	A
Surface Wind Stress	III	B
Vegetation/Surface Type	III	B

A - value to the government, if thresholds are exceeded and/or objective approached

B - value to the government, if thresholds are exceeded and/or objective approached, however, should not be design driver

Algorithms

Details available in Algorithm Theoretical Basis Document (ATBD)

Maximum likelihood technique - Similar approach used in CrISS

- Temperature profile
- Water vapor profile
- Precipitable water
- Total water content
- Pressure profile
- Cloud parameters
- Surface emitting temperature LST, IST
- Surface spectral emissivity
- Soil moisture (AMSR type approach)

Regression, best fit value - Approach similar to SSMI, TMI, AMSR/Windsat)

•Sea surface wind speed

•Sea surface temperature

•Sea surface wind direction

Others

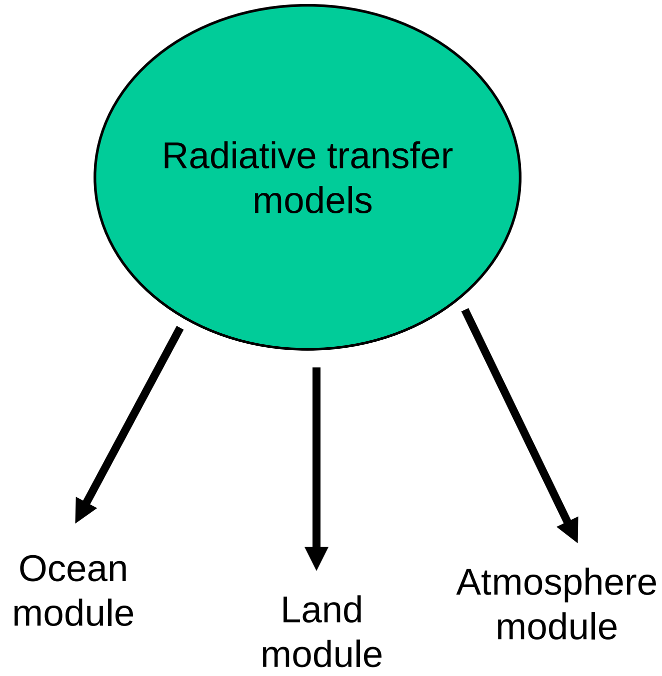
•Spectral gradients (snow cover)

•Polarization ratios (sea ice concentration and ice type, Fresh water ice concentration)

•Neural networks (precipitation rate for land, cloud liquid water from precipitating clouds over land)

•Decision trees (vegetation surface types)

•Ad-hoc/iterative solution (SS wind stress, precipitation over ocean)



•Minimization of cost function

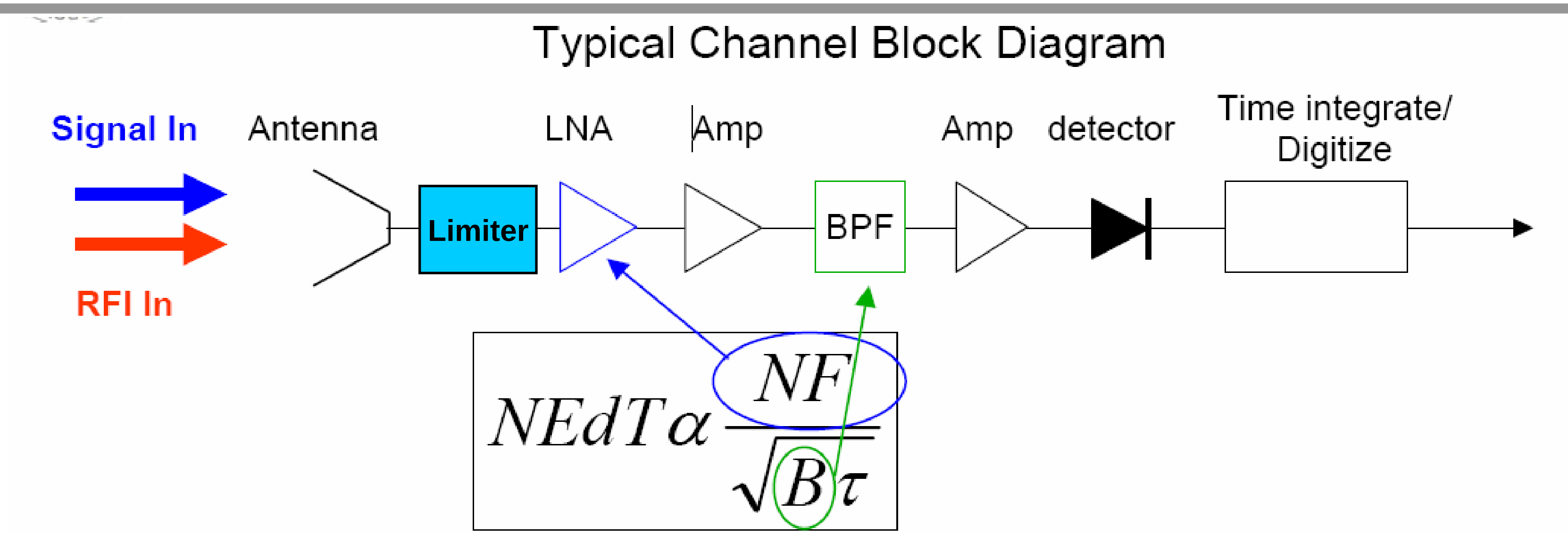
$$J(\mathbf{x}) = \left(\mathbf{y}^m - \mathbf{y}(\mathbf{x})\right)^T \mathbf{S}_y^{-1}\left(\mathbf{y}^m - \mathbf{y}(\mathbf{x})\right) + \left(\mathbf{x} - \mathbf{x}_0\right)^T \mathbf{S}_x^{-1}\left(\mathbf{x} - \mathbf{x}_0\right)$$

x is a vector containing temperature profile, water vapor profile, cloud parameters, surface temperature, surface emissivity

•Solution is obtained by iteration

$$\mathbf{x}_{n+1} = \mathbf{x}_0 + \mathbf{S}_x \mathbf{K}_n^T \left(\mathbf{K}_n \mathbf{S}_x \mathbf{K}_n^T + \mathbf{S}_\varepsilon\right)^{-1} \left[(\mathbf{y}^m - \mathbf{y}_n) + \mathbf{K}_n(\mathbf{x}_n - \mathbf{x}_0)\right]$$

Instrument Sensitivity & Survivability



- NEDT is how many degrees Kelvin the scene brightness has to change before the instrument can "see" the difference – a lower number is better
- For survivability (protecting the LNA against high power signals), a limiter may be put in front of the LNA. A Limiter is an RF surge protector –it lets low power signals like the radiometric "signal" through while blocking high power signals like radar pulses
- Adding a limiter has some downside
  - Adding limiter between the antenna and the LNA increases noise figure and degrades NEDT, thus degrading weather product accuracy
  - Limiter will respond to out-of-band signals, and in so doing degrade in-band performance

RFI Analysis Results

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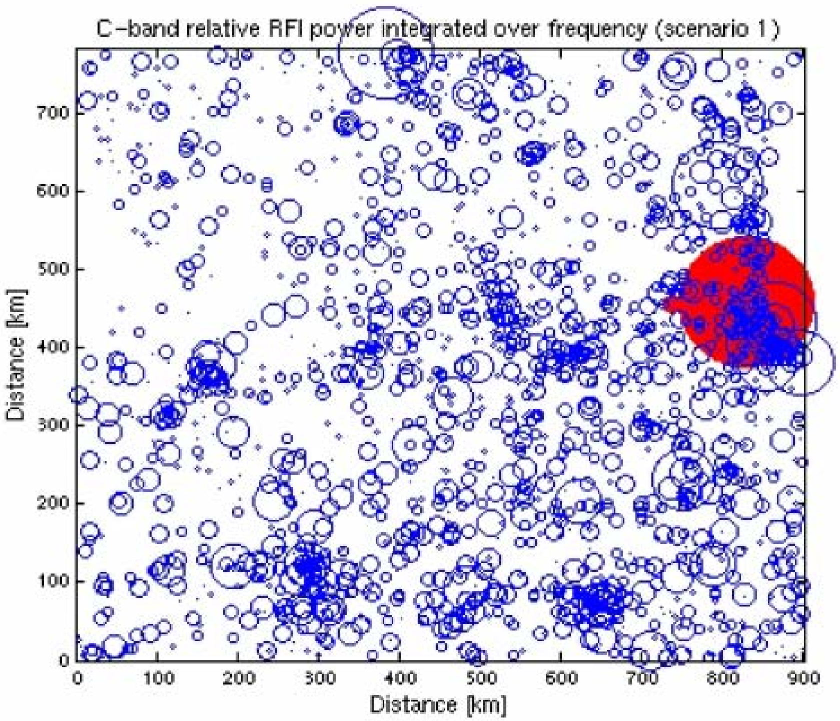
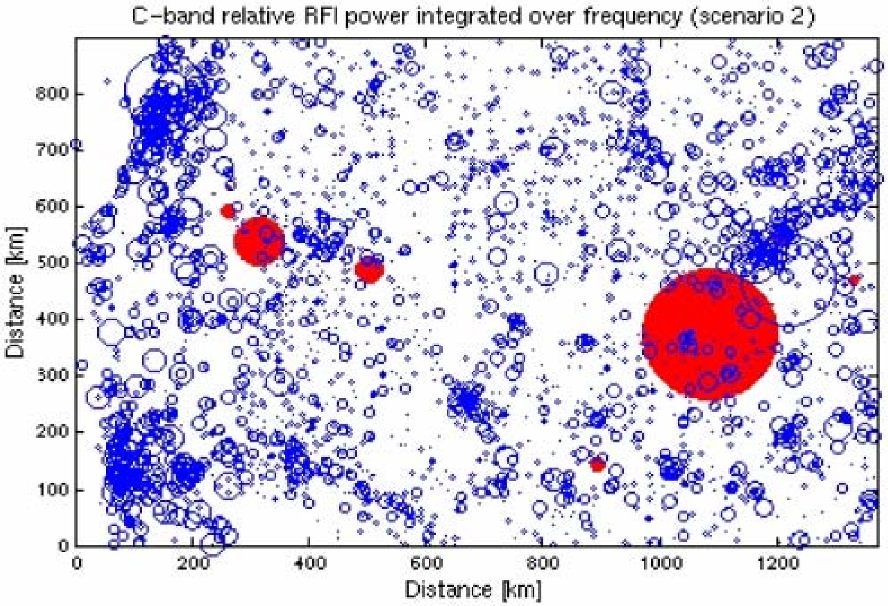
Spatial Distributions of RFI Sources for Scenario 1 & 2





- Circles are scaled by power integrated over 6400-7600 MHz
  - Scenario 1, 2, and 3 are scaled separately
  - CW (blue) and pulsed sources (red) are scaled separately